Ion kinetics and turbulence dissipation in the solar wind

Sofiane Bourouaine,
Eckart Marsch and Fritz Neubauer

Max-Planck Institute for Solar System Research

Vienna, March 2011

Outline

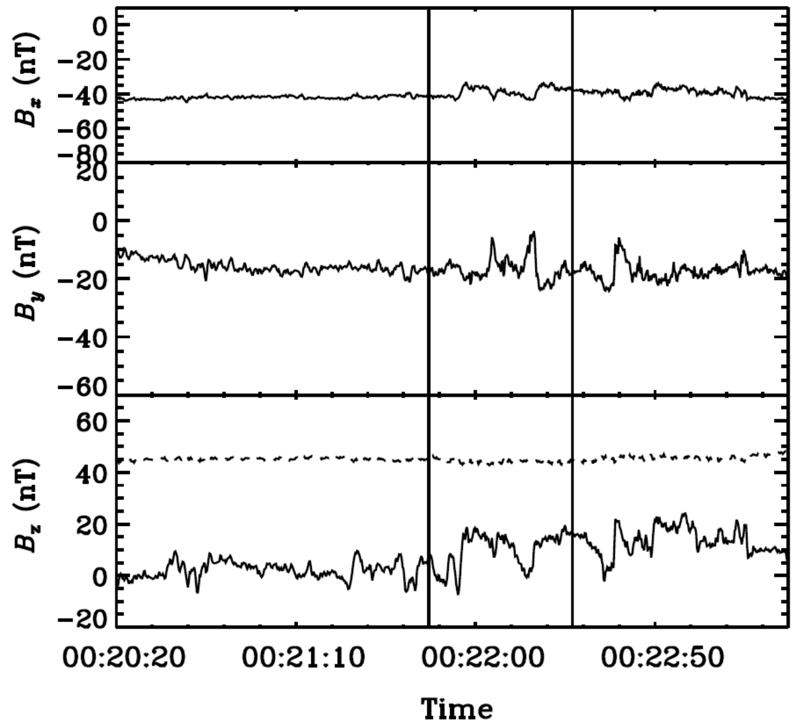
- Plasma and magnetic-field measurements
- Correlation between $\frac{T_{\perp p}}{T_{\parallel p}}$ and the power of the turbulent fluctuations
- Preferential acceleration and heating of alpha particles
- Signature of alpha-particle heating by resonant wave-particle interactions
- Summary

Plasma and magnetic-field measurements

Helios Measurements:

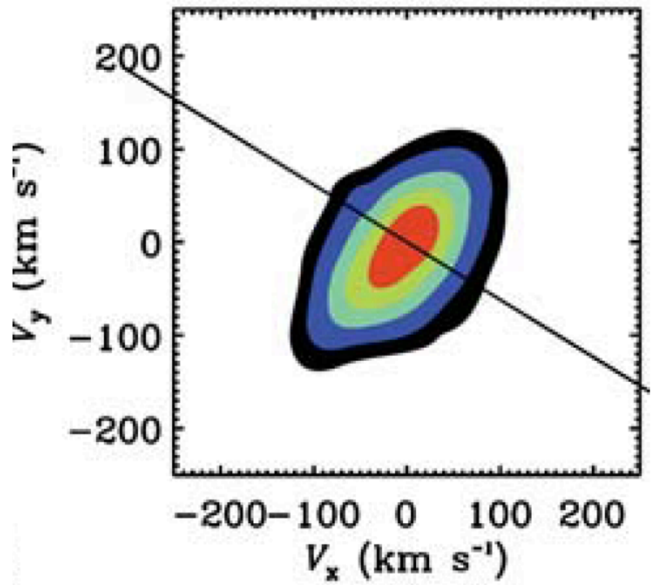
DOY 105 (1976), at 0.29 AU

solar ecliptic coordinates system



High-resolution magnetic field vector measurements, Nyquist between 2 and 4Hz

Proton core VDF



Measurement of Ion VDF
Cadence 40.5 s

Bourouaine et al. 2010

Plasma and magnetic-field measurements

The frequency range to be considered

We consider the power of the fluctuations having frequencies between $[0.01 f_p^{'}, f_p^{'}]$ in the space-craft frame.

$$\delta B^2 = \int_{0.01 f_p'}^{f_p'} \delta B_\omega^2 d\omega$$

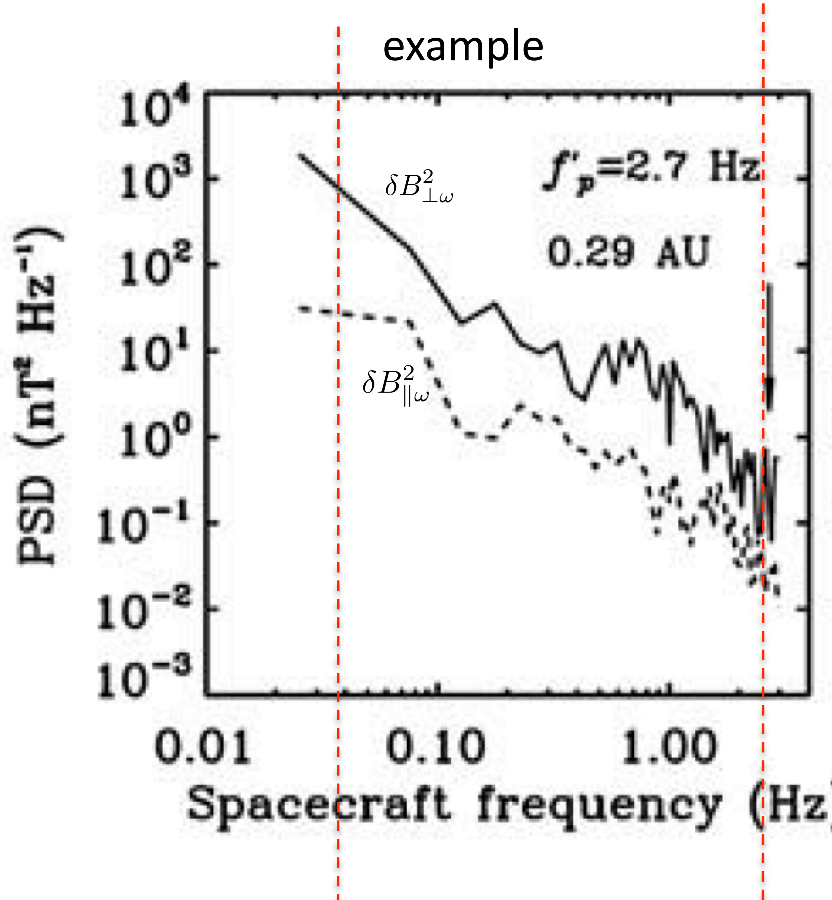
Taylor's hypothesis

$$f_{sc} \simeq k V_{sw}$$

then the wave-number interval considered here is $[0.01 - 1] k_p$ (inertial range)

$k_p = 1/l_p$ l_p is the proton inertial length

example



$$f_p^{'} \simeq M_A f_p$$

Bourouaine et al. 2010

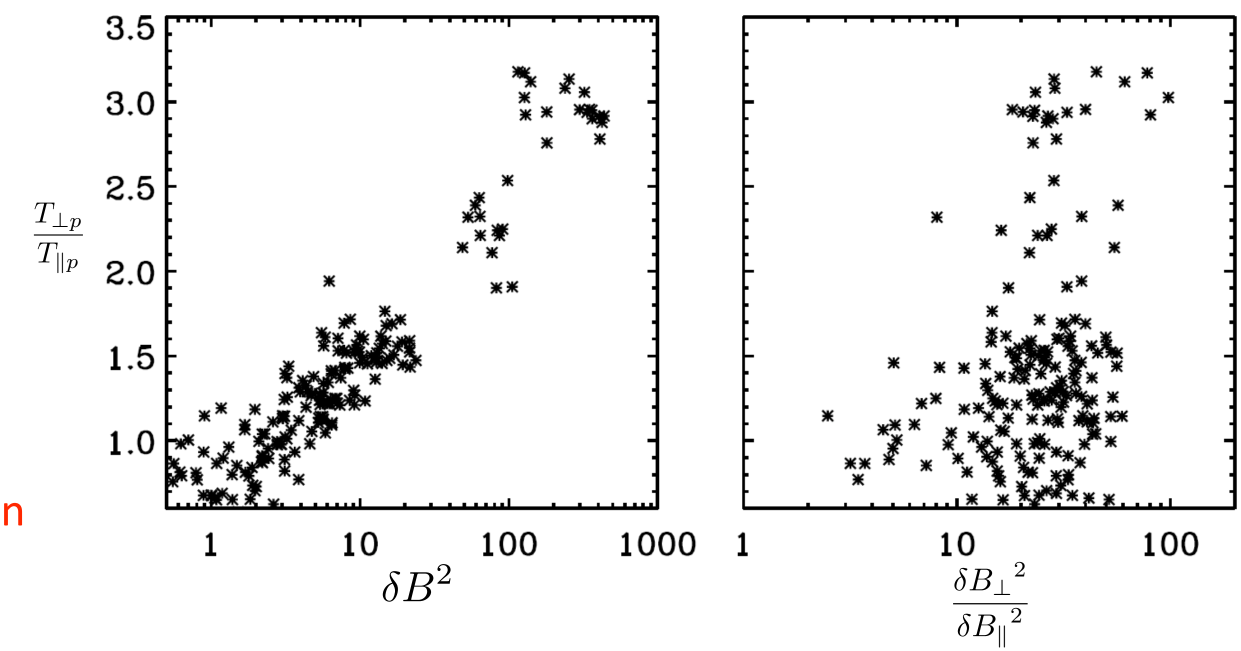
Correlation between $\frac{T_{\perp p}}{T_{\parallel p}}$ and δB^2 (fast solar wind)

Helios 2 data set (1976),
DOY : 36, 46, 51, 61, 67, 76,
95 and 105

Distances between 0.29 and
0.95 AU

The oscillations are mostly transverse (most likely are Alfvén waves)

Alfvén waves (with period higher than 40 s) are observed extensively in fast solar wind (Tu and Marsch 1995)



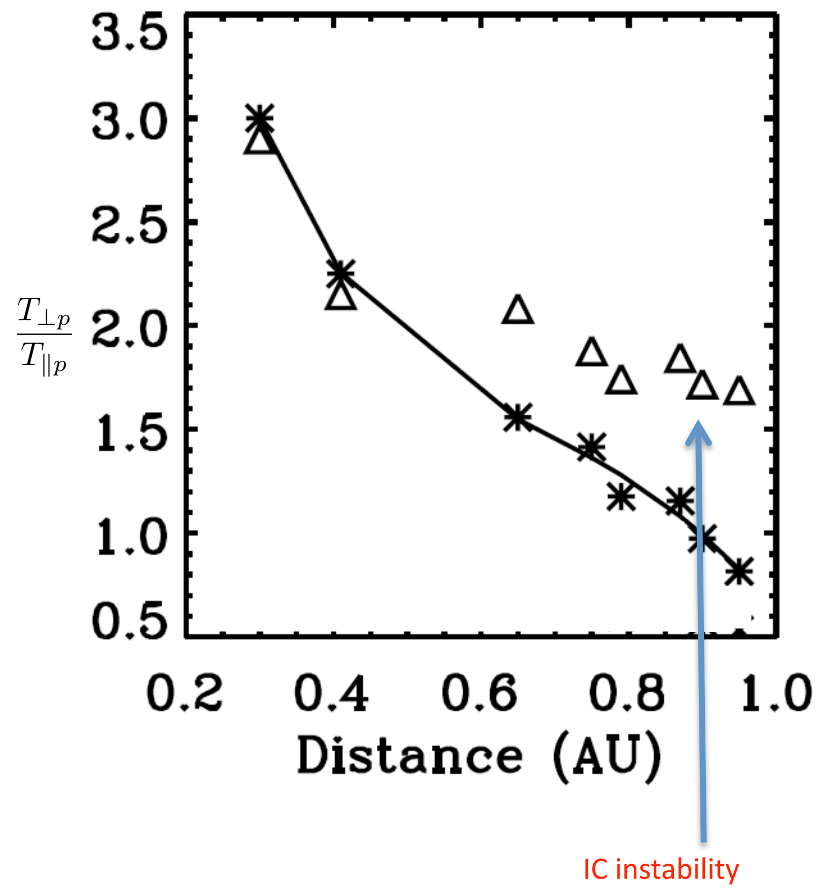
A slight correlation between $\frac{T_{\perp p}}{T_{\parallel p}}$ and $\frac{\delta B_{\perp}{}^2}{\delta B_{\parallel}{}^2}$

Bourouaine et al. 2010

Correlation between $\frac{T_{\perp p}}{T_{\parallel p}}$ and δB^2 (fast solar wind)

Thresholds of proton temperature anisotropy for IC instability obtained from the theory of linear plasma instability assuming proton bi-Mawellian VDF

We expect that the plasma is highly unstable near the sun due to large proton temperature anisotropy.



Bourouaine et al. 2010

What causes the correlation between the proton temperature anisotropy and the wave power?

The standard picture: temperature anisotropy is caused by ion-cyclotron wave dissipation process.

However,

- The perpendicular proton heating could be a result of :

. Stochastic heating (Chandran et al. 2010) by low-frequency turbulent fluctuations having scales near the proton gyro-radius

. Non-resonance heating (heating by low-frequency Alfven waves) Wu and yoon 2007 ; Bourouaine et al. 2008

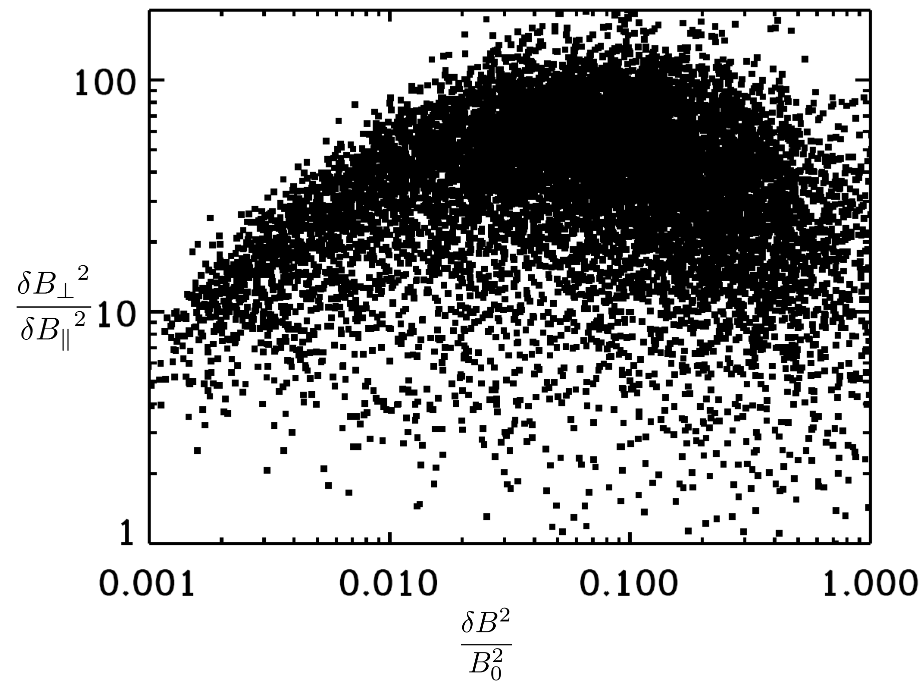
Preferential acceleration and heating of alpha particles

Preferential acceleration and heating of alpha particles

Data set to be considered

- Helios 2 dataset at about 0.7 AU
- Continuous measurements (1976) with DOY numbers, 67 to 73

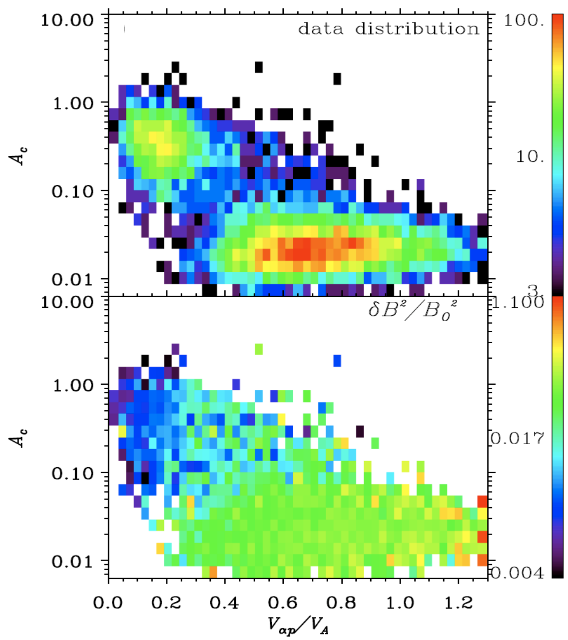
In this data set the helium ions have relatively a good statistical count and are clearly separated from proton VDFs

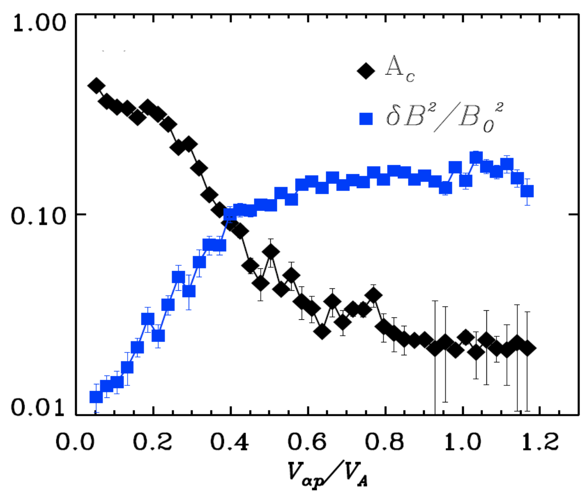


The oscillations are mainly transverse

Preferential acceleration and heating of alpha particles

Preferential acceleration of alpha-particles:





The collision age, $A_c = l/(V_{sw}\tau_{\alpha p})$

The ion differential velocity,

$$V_{\alpha p} = |\vec{V_\alpha} - \vec{V_p}|$$

- High wave power corresponds to high normalized ion differential speed.

- Generally, there is an anti-correlation between the collision age and the normalized wave power.

Could the turbulent fluctuations be responsible on the local acceleration of the helium ions?

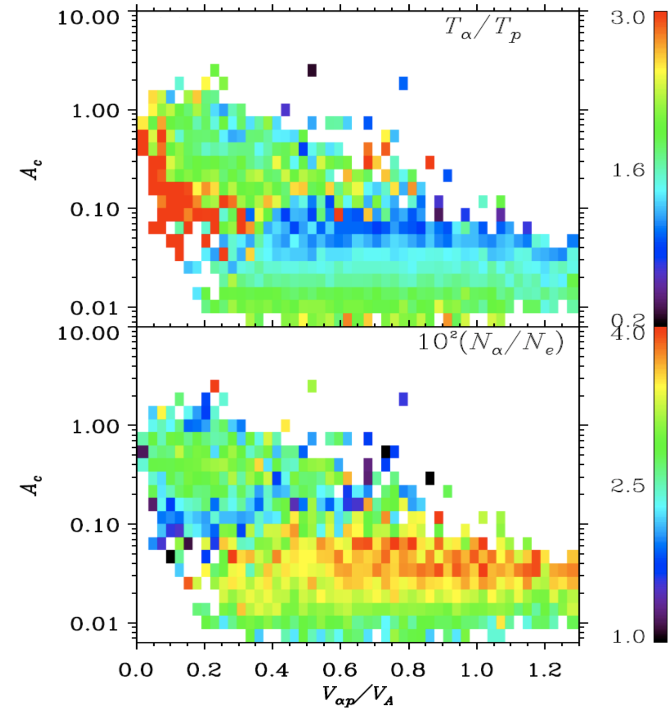
Preferential acceleration and heating of alpha particles

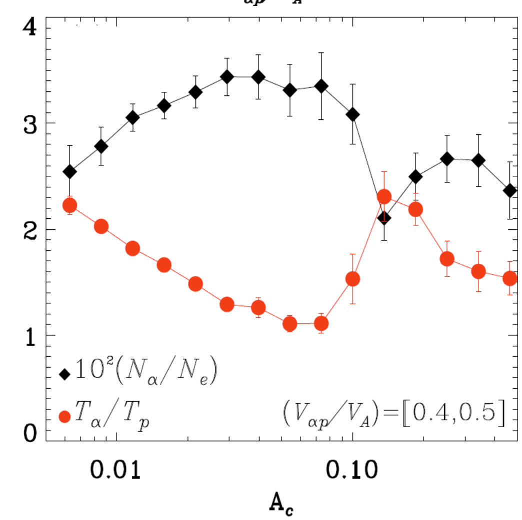
Preferential heating of alpha-particles:

- It seems that the ratio $\frac{T_\alpha}{T_p}$ is not related to the normalized wave power.

- However, the temperature ratio $\frac{T_\alpha}{T_p}$ anti-correlates with the the Helium abundance.

- Collisions seems to be less efficient for the equalization of the ion temperatures



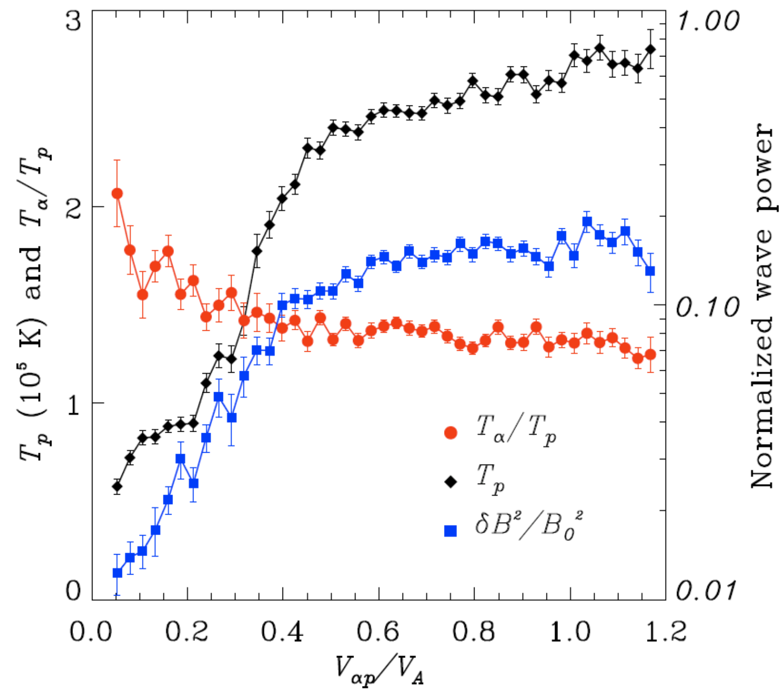


Preferential acceleration and heating of alpha particles

Ion temperatures:

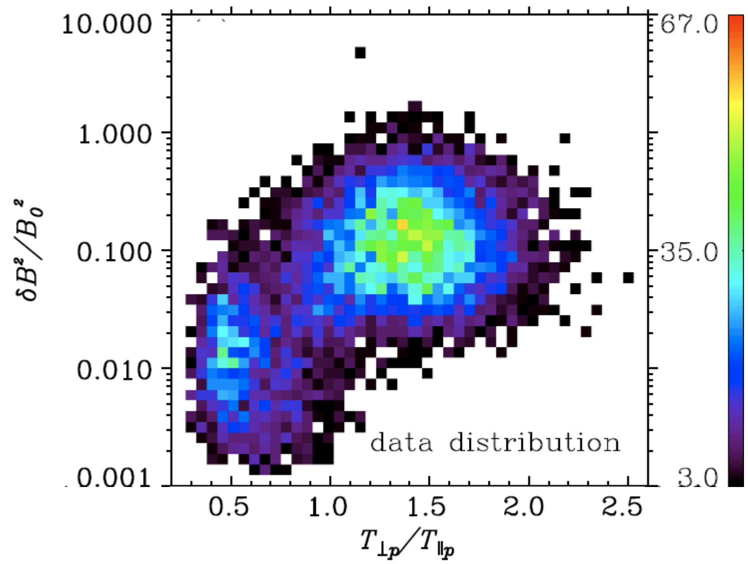
- The heating of both ion species correlates with the normalized wave power.

However, the preferential heating of Helium ions seems not to be strictly connected to the wave power.



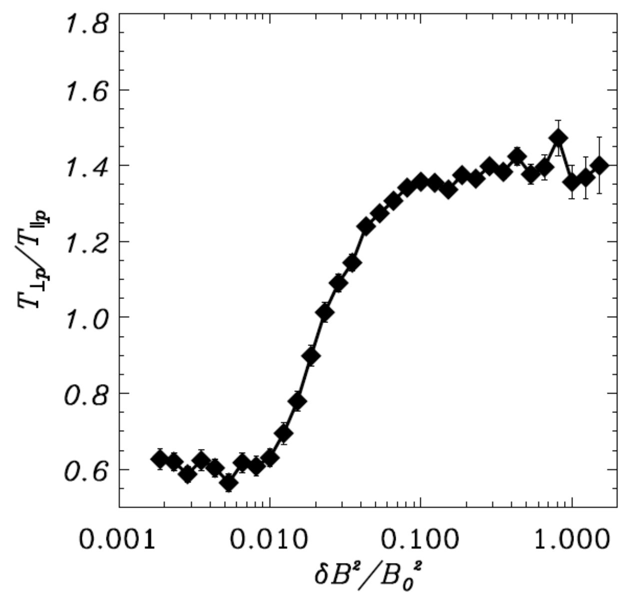
Signature of alpha-particle heating by resonant wave-particle interactions

Signature of alpha-particle heating by resonant wave-particle interactions



Proton temperature anisotropy:

There is again a correlation between the normalized and the proton temperature anisotropy (as we found in our previous work with other dataset)



The temperature anisotropy is roughly constant when the normalized wave power is below 0.01 or higher than 0.1.

Signature of alpha-particle heating by resonant wave-particle interactions

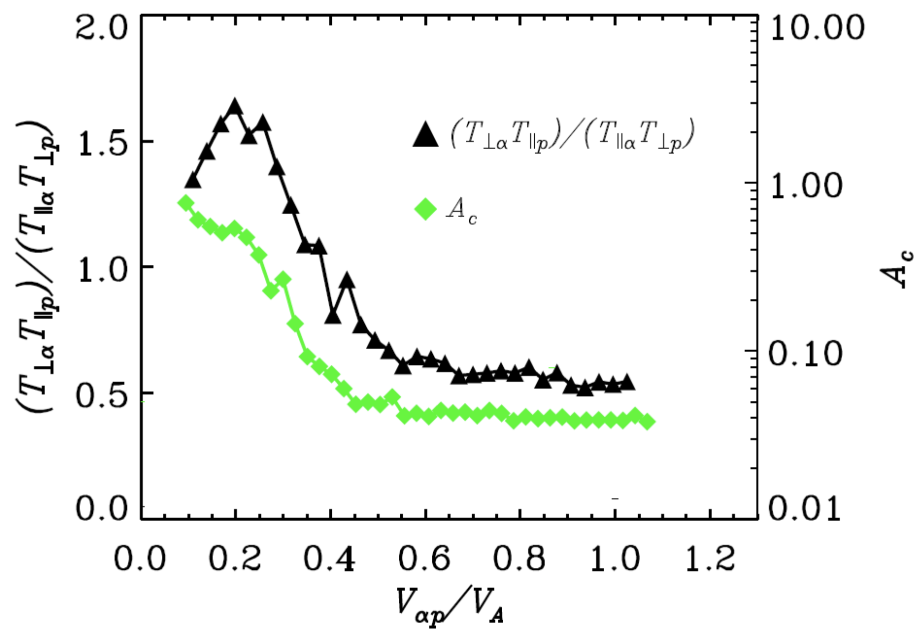
Helium temperature anisotropy:

Here we compare the temperature anisotropy of Helium ion with that one proton by considering the following quantity,

$$\frac{T_{\perp\alpha}/T_{\|\alpha}}{T_{\perp p}/T_{\|p}}$$

When $\frac{V_{\alpha p}}{V_A} \lesssim 0.4$ $\longrightarrow$ $\frac{T_{\perp\alpha}/T_{\|\alpha}}{T_{\perp p}/T_{\|p}} > 1$

When $\frac{V_{\alpha p}}{V_A} > 0.5$ $\longrightarrow$ $\frac{T_{\perp\alpha}/T_{\|\alpha}}{T_{\perp p}/T_{\|p}} < 1$



Is this behavior has something to do with ion cyclotron heating mechanism?

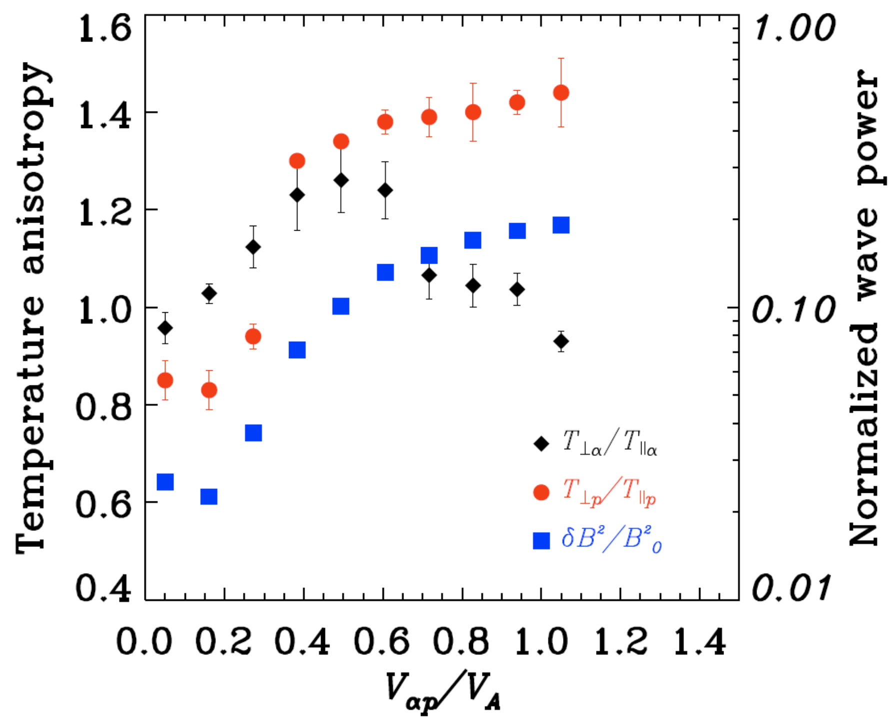
Signature of alpha-particle heating by resonant wave-particle interactions

ion temperature anisotropies:

- The perpendicular heating of proton ultimately connected to the normalized wave power and it is not affected by the ion differential speed.

- When $\frac{V_{\alpha p}}{V_A} \lesssim 0.5$ → $\frac{T_{\perp\alpha}}{T_{\parallel\alpha}}$ increases with the normalized wave power

- When $\frac{V_{\alpha p}}{V_A} > 0.5$ → $\frac{T_{\perp\alpha}}{T_{\parallel\alpha}}$ declines despite the high values of the normalized wave power.

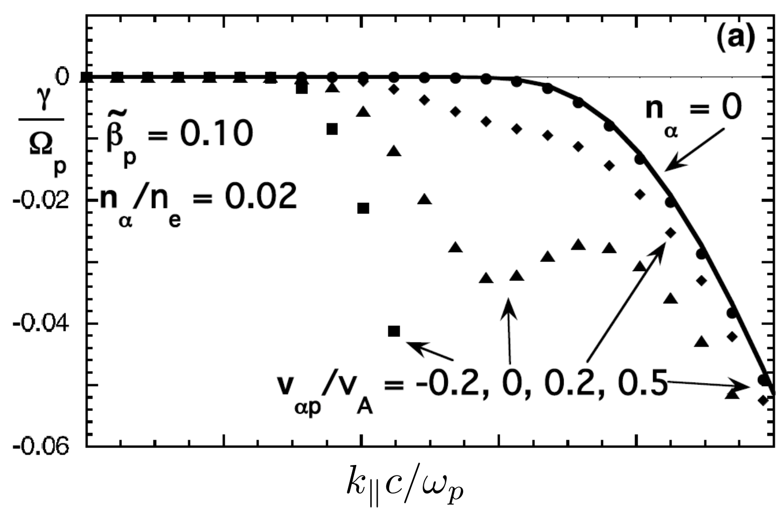


The heating (or the ion-cyclotron heating) of ions is connected to the wave power (the turbulence)

Signature of alpha-particle heating by resonant wave-particle interactions

Damping of AIC waves versus $\frac{V_{\alpha p}}{V_A}$

simulation



The damping of AIC waves through helium ion-cyclotron resonance ceases when $\frac{V_{\alpha p}}{V_A} \geq 0.5$

↓

Helium ions get perpendicularly heated when they are in resonance with AIC waves. This scenario occurs when $\frac{V_{\alpha p}}{V_A} < 0.5$

Gary et al. (2005)

Summary

- The proton temperature anisotropy and the normalized ion differential speed strictly correlate with the total power of the turbulent fluctuations.
- There is a clear anti-correlation between the alpha-to-proton relative temperatures and the helium ion abundance.
- When the normalized differential ion speed is a value of about 0.5, then the perpendicular alpha-particle temperature anisotropy correlates positively with the relative power of the transverse waves. Otherwise, the alpha-particle temperature anisotropy tends to decrease towards values below unity, despite the presence of transverse waves with relatively large amplitudes. This seems to be in a good agreement with the predictions of ion heating mechanism based on resonant wave-particle interactions.

Possible scenario:

Nonresonant ion heating by low-frequency Alfvén waves $(\omega \ll \Omega_p)$

Under low plasma beta condition

$$\frac{\partial f_j}{\partial \tau} = \frac{1}{4v_\perp}\frac{\partial}{\partial \alpha}\left(v_\perp \frac{\partial f_j}{\partial \alpha}\right) \qquad \text{(QLT)}$$

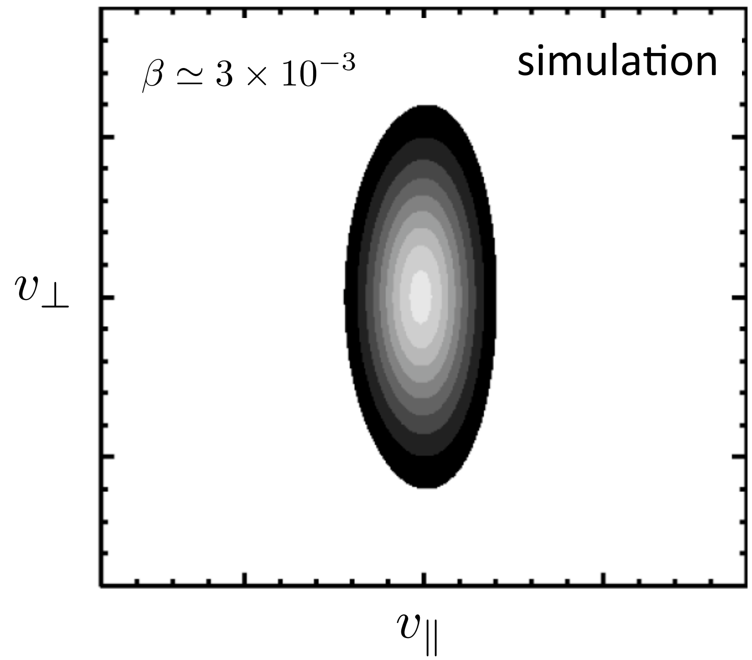
$$\tau = \int \frac{\delta B_k^2}{B_0^2} dk$$

Wu and Yoon (2007); Bourouaine et al. (2008)

$$T_{\perp i}/T_{\perp p} \propto m_i/m_p$$

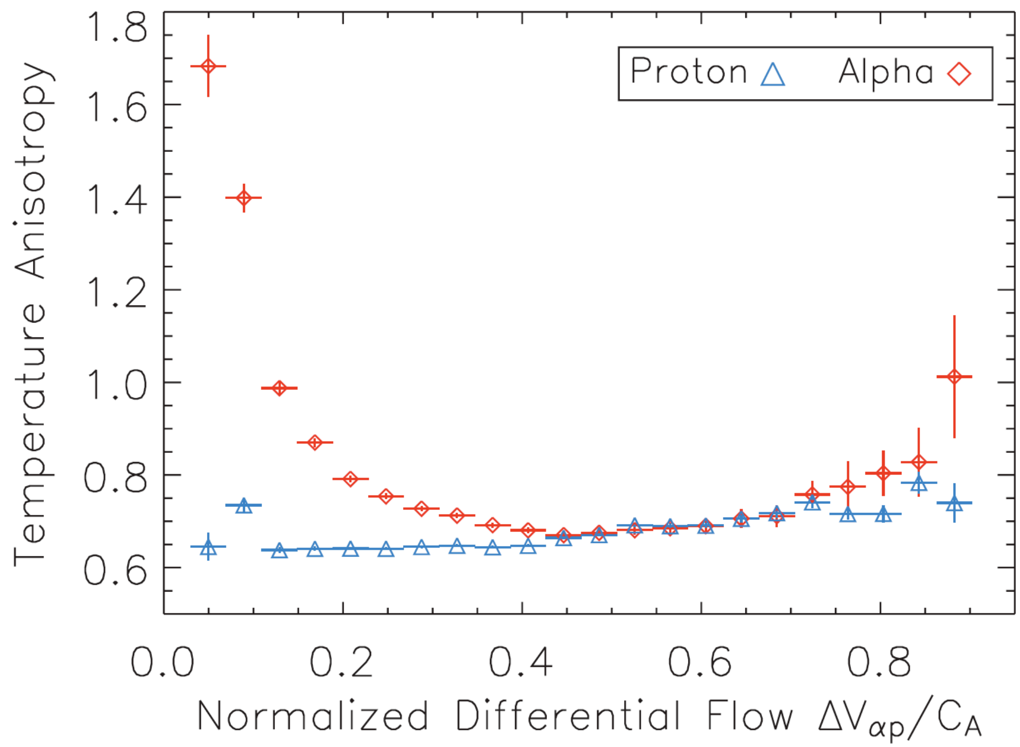
Heavy ions are preferential heated

Anisotropic Helium VDF

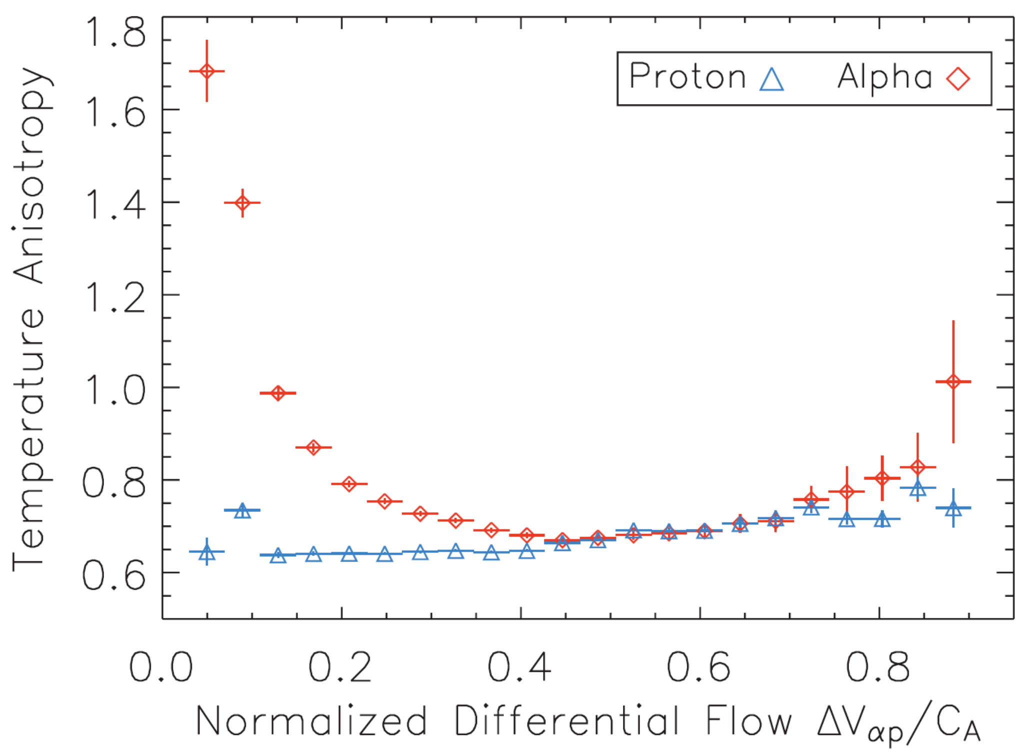


Bourouaine et al. (2008)

However, this process leads to the so-called "apparent heating" or "stochastic heating" since it is reversible process (there is no wave dissipation)!!



Kasper et al. 2008



Kasper et al. 2008

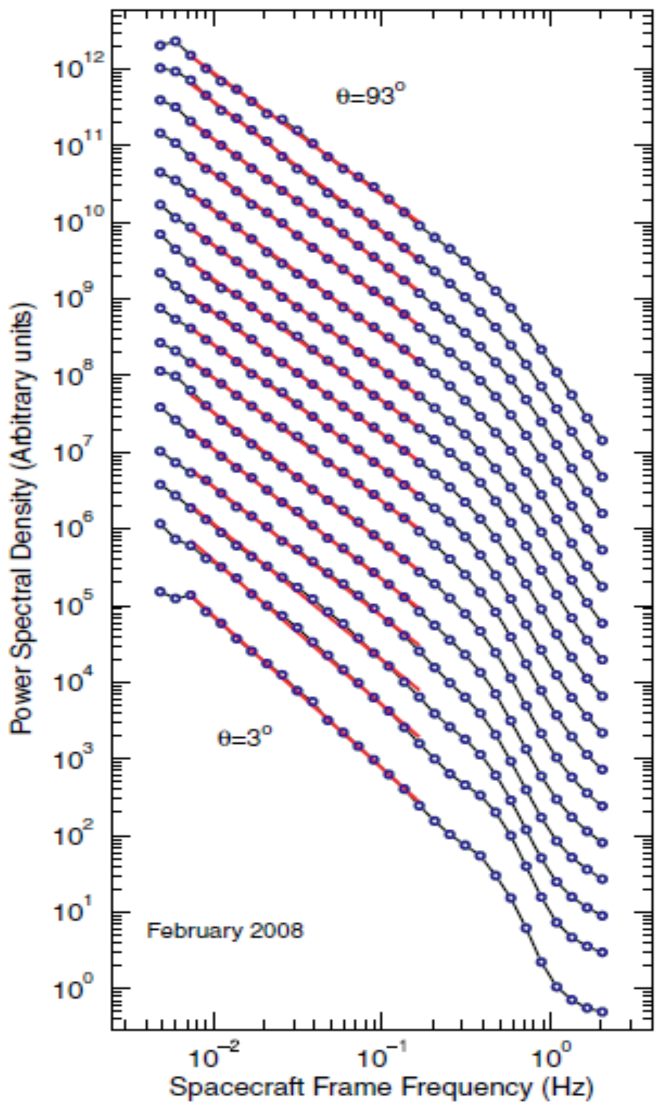
Solar wind turbulence (measurements)

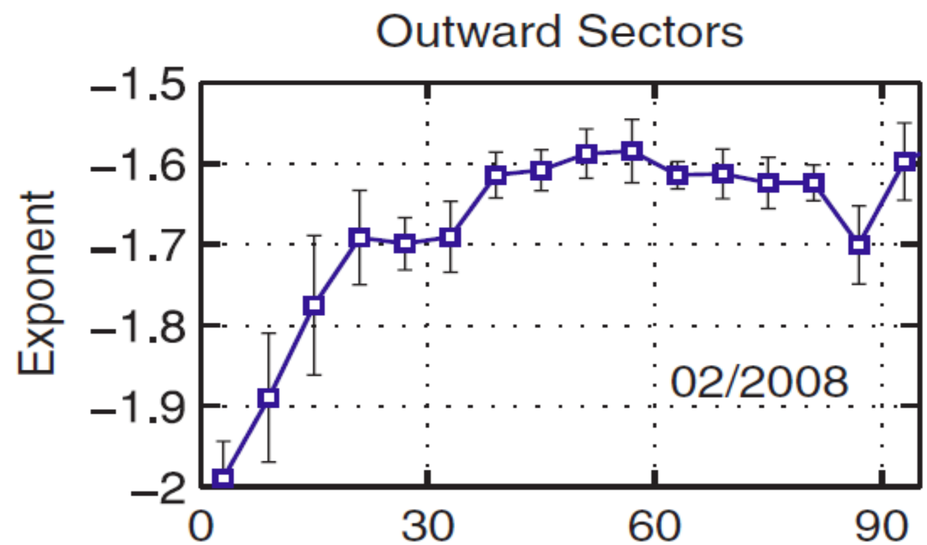
- What are the characteristics of the solar wind turbulence in the inertial regime (e.g., the power anisotropy, the steepness of the PSD, frequency and the type of the dominant modes etc.....) ?

- If the Alfvén waves are the most dominant waves in the IR, which waves are dominant in the dissipation regime?

Unfortunately, from direct measurements we can get answer on all questions

1.2 Θ_{VB} dependence of reduced 1D-PSD of solar wind turbulence





Podesta (ApJ, 2009)

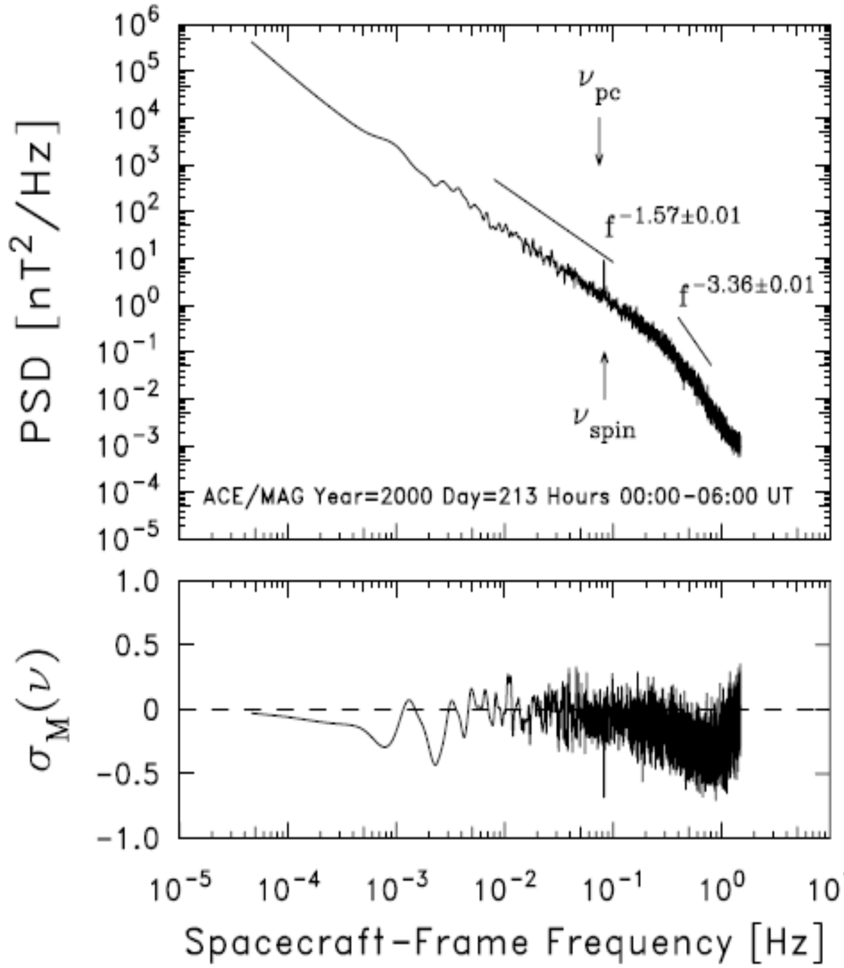
The theta-variation of the power-law exponent seems to be consistent with Critical-Balance prediction.

How do the fluctuations dissipate? (dissipation range)

- The reduced magnetic helicity become negative at the dissipation range
- If we assume that the upward propagating waves are the dominant modes in the dissipation regime, then there is change in the wave polarization

- Interpretation: Most of the upward (left-handed polarized) fluctuations get damped in the dissipation range, and only the upward (right-handed polarized) fluctuations remains

- Two possibilities,
- 1 - one is that the waves were parallel ICA waves get damped via proton-cyclotron absorption.
- 2 – Conversion from Alfvén to Kinetic Alfvén waves



Solar wind turbulence

SW plasma is turbulent and shows fluctuations with solar rotation period up to electron plasma period (i.e., 10^-6 Hz to ~10^4 Hz)

Fundamental issues of SW turbulence have been addressed:

-The nature and the properties of the fluctuations

- The mechanisms of the turbulent cascade of energy through the inertial range, and the corresponding "dissipation" at the smallest scales near the local ion gyro-frequency

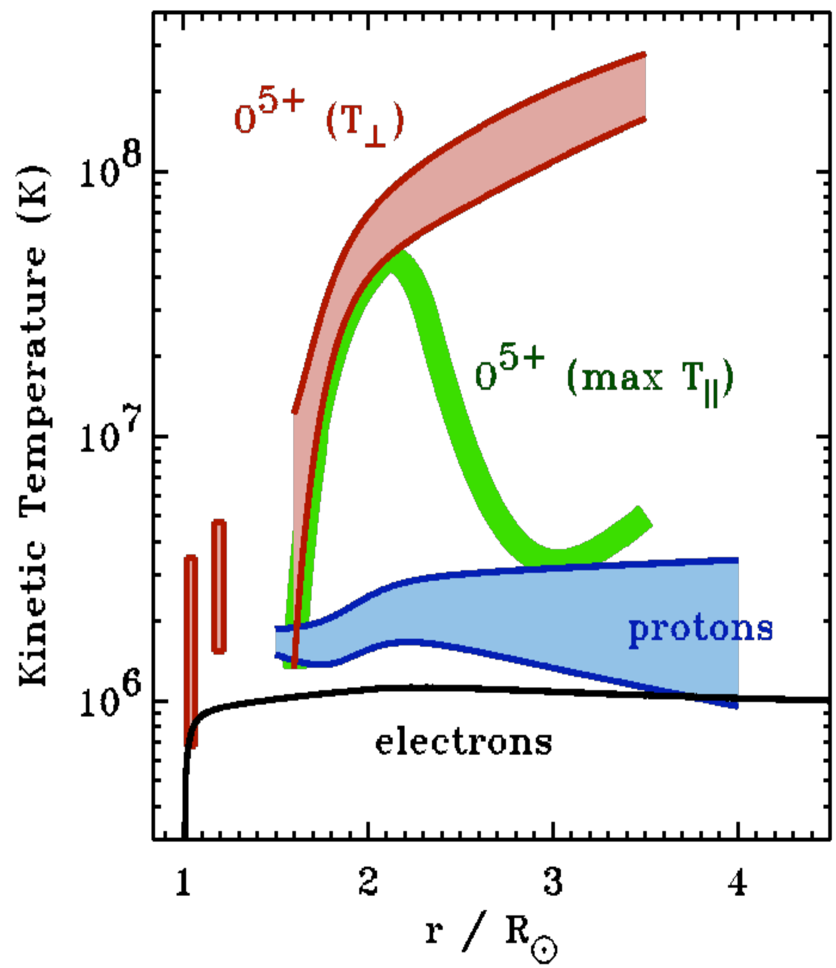
However, two of the primary problems of solar wind MHD turbulence that still remain a puzzle are the nature of the nonlinear energy cascade and the strong intermittent character of solar wind fluctuations in the inertial range.

The impact of UVCS

UVCS has led to new views of the collisionless nature of solar wind acceleration. Key results include:

- The fast solar wind becomes **supersonic** much closer to the Sun (~2 R_s) than previously believed.
- In coronal holes, heavy ions (e.g., O^{+5}) both flow **faster** and are **heated** hundreds of times more strongly than protons and electrons, and have **anisotropic temperatures**. (e.g., Kohl et al. 1997,1998)

$$\left\{ \begin{array}{ccc} T_{\rm ion} \gg & T_p & > T_e \\ (T_{\rm ion}/T_p) & > & (m_{\rm ion}/m_p) \\ T_\perp & \gg & T_\parallel \\ u_{\rm ion} & > & u_p \end{array} \right\}$$

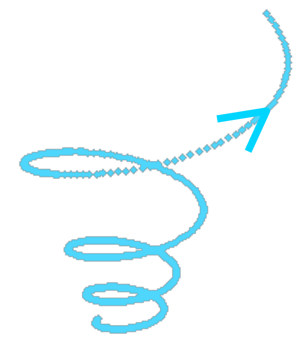


Ion cyclotron waves in the corona

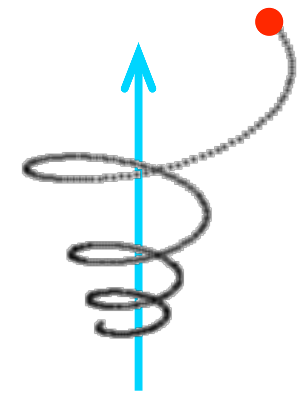
- UVCS observations have **rekindled theoretical efforts** to understand heating and acceleration of the plasma in the (collisionless?) acceleration region of the wind.

- Ion cyclotron waves (10 to 10,000 Hz) suggested as a natural energy source that can be tapped to preferentially heat & accelerate heavy ions.

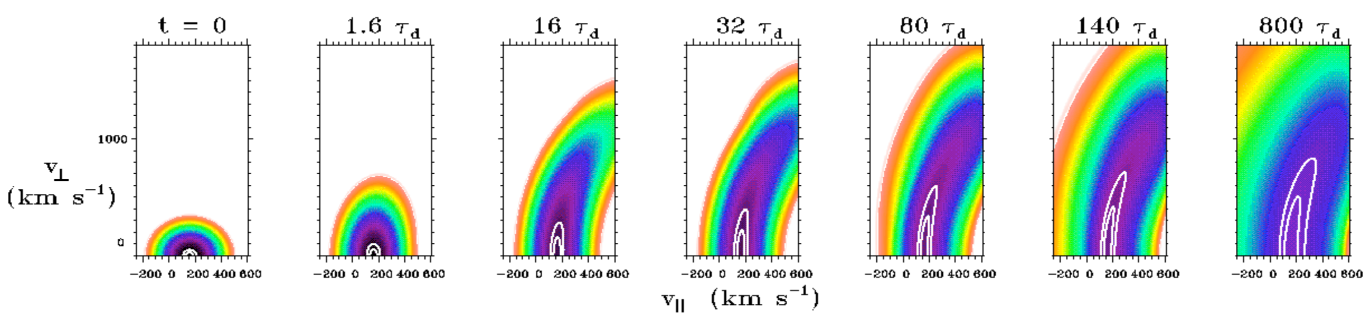
- Dissipation of these waves produces **diffusion** in velocity space along contours of ~constant energy in the frame moving with wave phase speed:



Alfvén wave's oscillating E and B fields



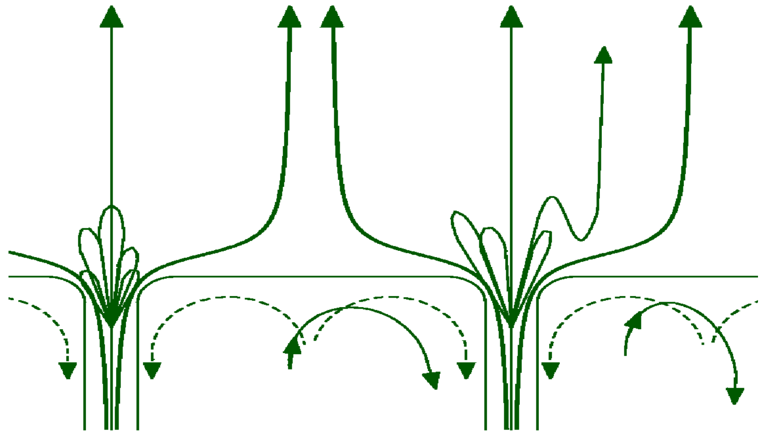
ion's Larmor motion around radial B-field



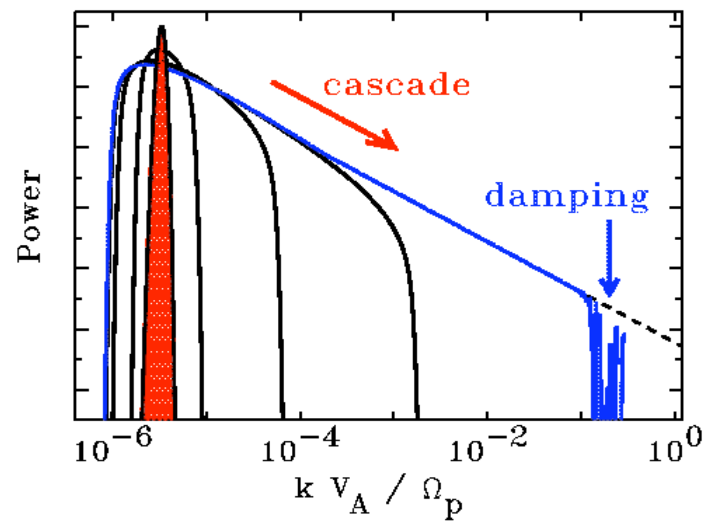
lower Z/A

faster diffusion

Where do cyclotron waves come from?



(1) **Base generation** by, e.g., "microflare" reconnection in the lanes that border convection cells (e.g., Axford & McKenzie 1997).



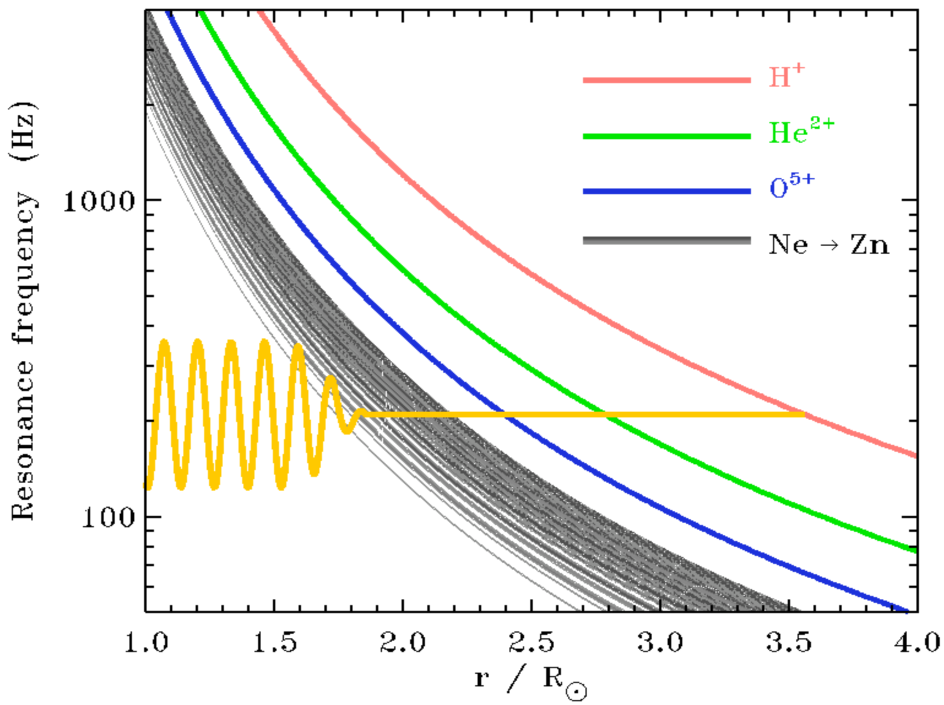
(2) **Secondary generation**: low-frequency Alfvén waves may be converted into cyclotron waves gradually in the corona.

Both scenarios have problems . . .

"Opaque" cyclotron damping (2)

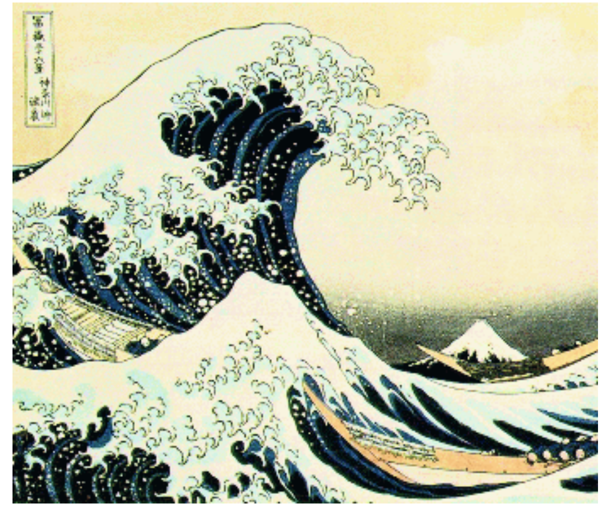
- However, minor ions can damp the waves as well:

$$\Omega_{\rm ion} = \frac{Z_{\rm ion}}{A_{\rm ion}}\,\Omega_{\rm p} \;, \quad P \approx P_0\, e^{-\tau} \;, \quad \tau \approx 10^5 \left(\frac{m_{\rm ion} n_{\rm ion}}{m_{\rm p} n_{\rm p}}\right)$$



- Something very similar happens to resonance-line **photons** in winds of O, B, Wolf-Rayet stars!
- Cranmer (2000, 2001) computed "tau" for >2500 ion species.
- If cyclotron resonance is indeed the process that energizes high-Z/A ions, the wave power must be **replenished continually** throughout the extended corona.

MHD turbulence



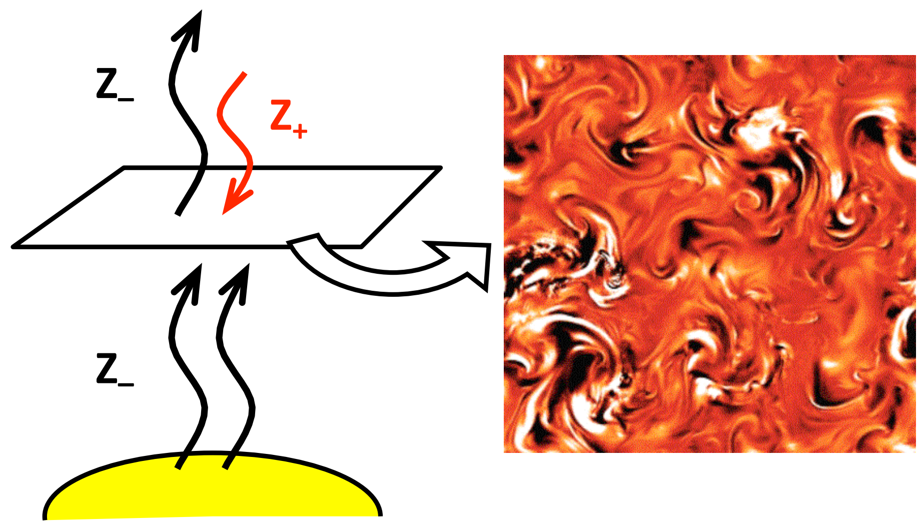
- It is highly likely that somewhere in the outer solar atmosphere the fluctuations become turbulent and **cascade** from large to small scales:

$$\mathcal{E}_{\rm out} = \frac{\rho\, {\rm v}_{\rm eddy}^3}{\ell_{\rm eddy}} \quad \rightsquigarrow \rightsquigarrow \rightsquigarrow \quad Q_{\rm heat} \approx \mathcal{E}_{\rm out}$$

- With a strong background field, it is easier to **mix** field lines (perp. to **B**) than it is to **bend** them (parallel to **B**).
- Also, the energy transport along the field is far from isotropic:

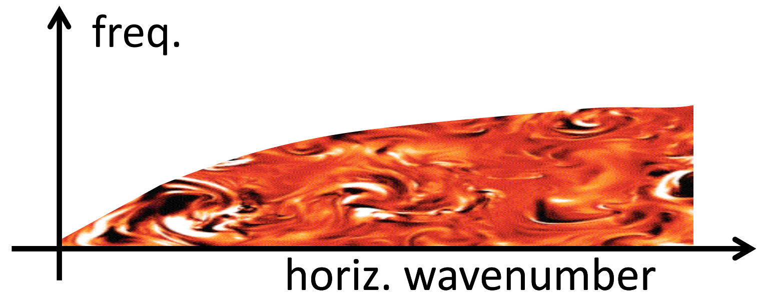
$$Q_{\rm heat} = \rho\, \frac{\langle Z_- \rangle^2 \langle Z_+ \rangle + \langle Z_+ \rangle^2 \langle Z_- \rangle}{4 L_\perp}$$

(e.g., Dmitruk et al. 2002)



But does turbulence generate cyclotron waves?

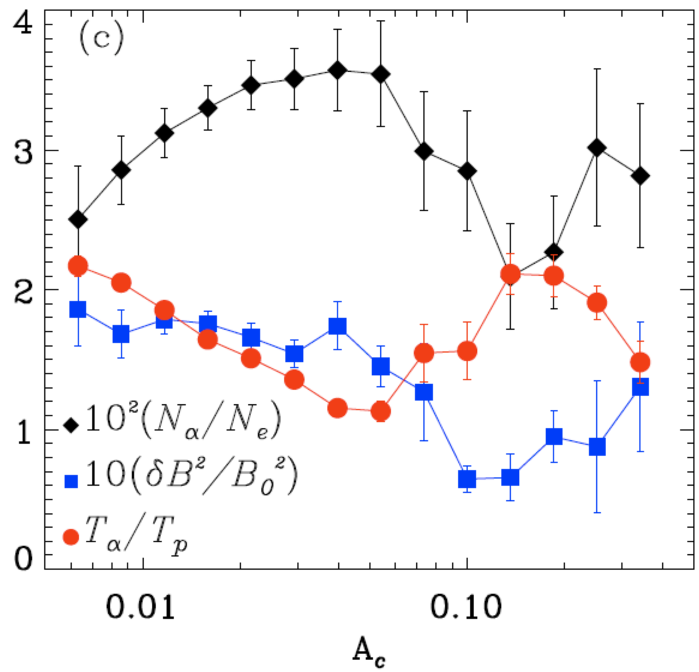
- Preliminary models say **"probably not"** in the extended corona. (At least not in a straightforward way!)
- In the corona, "kinetic Alfvén waves" with high $k_\perp$ heat electrons ($T_\parallel >> T_\perp$) when they damp linearly.



How then are the ions heated & accelerated?

- **Nonlinear instabilities** that locally generate high-freq. waves (Markovskii 2004)?
- Coupling with **fast-mode waves** that do cascade to high-freq. (Chandran 2006)?
- KAW damping leads to electron beams, further (Langmuir) turbulence, and Debye-scale **electron phase space holes**, which heat ions perpendicularly via "collisions" (Ergun et al. 1999; Cranmer & van Ballegooijen 2003)?

Some collisionless heating models:



Efficiency of collisions in solar wind

Locally, the Collisions can be estimated by the mean free path

$$\lambda_e = V_{the}\tau_e \sim 10^7 \text{ km}$$

Globally, the number Coulomb Collisions (or called the collision age) of particles during their travelling distances starting from the sun is

$$A_c = \frac{\tau_{tr}}{\tau_c}$$

Are the collisions existing in solar wind efficient to reduce the non-thermal features?

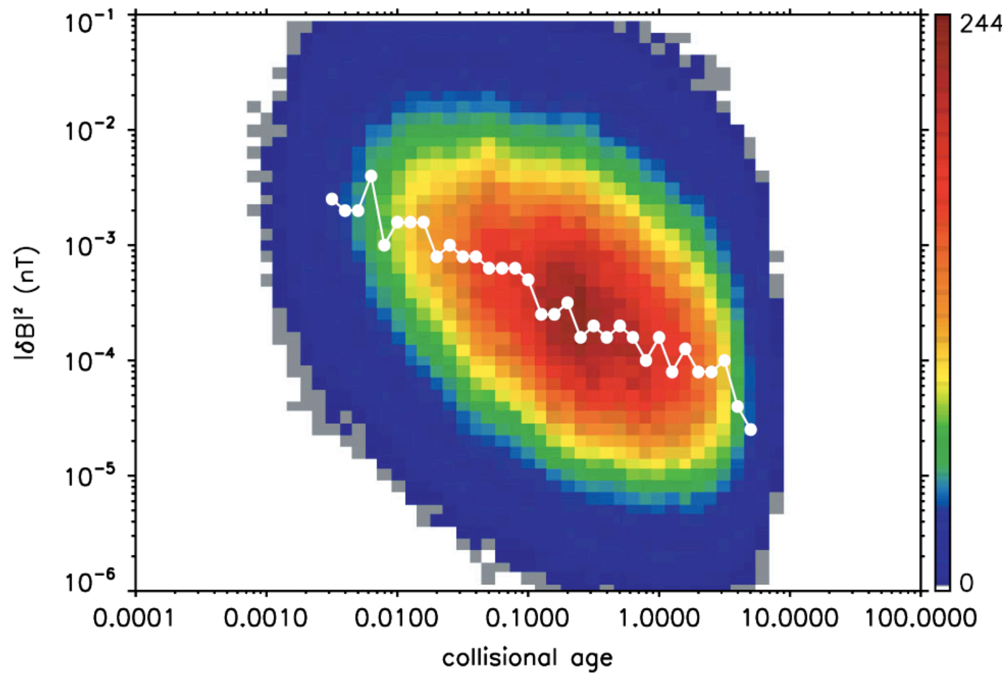
Temperature equilibration

Assuming two drifting Maxwelian velocity distributions for two species, Helium ion and proton, with $T_\alpha \neq T_p$

Hernandez et al. 1986

The averaged power of very high frequency waves ([0.3 – 5.5/11] Hz in SC frame) anti-correlates with collision age.

- The waves are excited via mirror or AIC or firehose instability due to temperature anisotropy which can occur when the collisions are relatively weak.



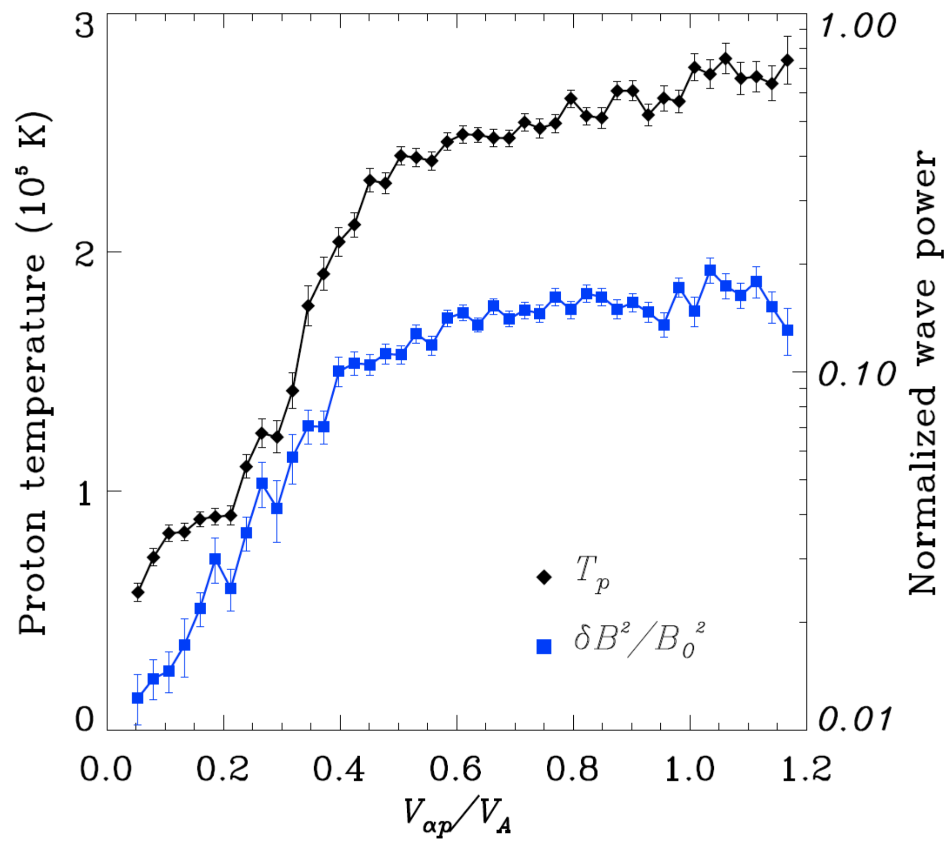
Data from Wind Spacecraft

Bale et al. 2009

- Averaged power of wave having frequencies between 0.01 and 1 in the plasma frame (or between 0.001 and 0.1 Hz in space-craft frame)

- The heating of protons is ultimately connected to the power of transverse waves

- The waves (or at least part of them) may cascade to smaller scale then dissipate

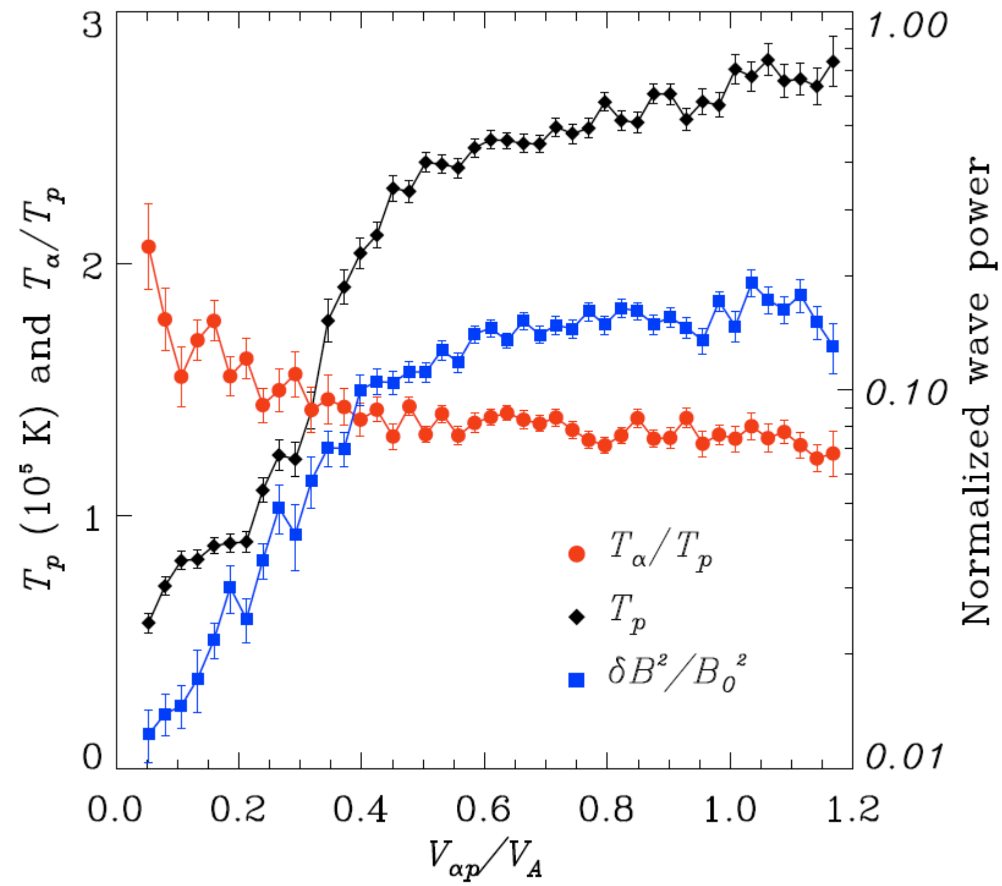


- Helium ions are preferentially heated than protons.

- When $\frac{V_{\alpha p}}{V_A} \leq 0.6$ the ratio $\frac{T_\alpha}{T_p}$ decreases as the ion differential speed increases

- When $\frac{V_{\alpha p}}{V_A} > 0.6$ the ratio $\frac{T_\alpha}{T_p}$ Is almost constant as the ion differential speed increases

Can this property be a signature of ion heating by AIC waves?

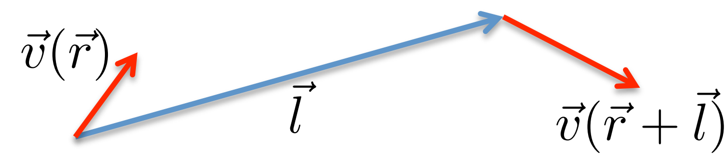


Scaling theory of turbulence

<u>Hydrodynamic turbulence (Kolmogorov turbulence)</u>

- Isotropic turbulence, i.e., $\delta v(\vec{l}) = \delta v(l)$

$$\delta v(\vec{l}) = < |\vec{v}(\vec{r}+\vec{l}) - \vec{v}(\vec{r})| >$$



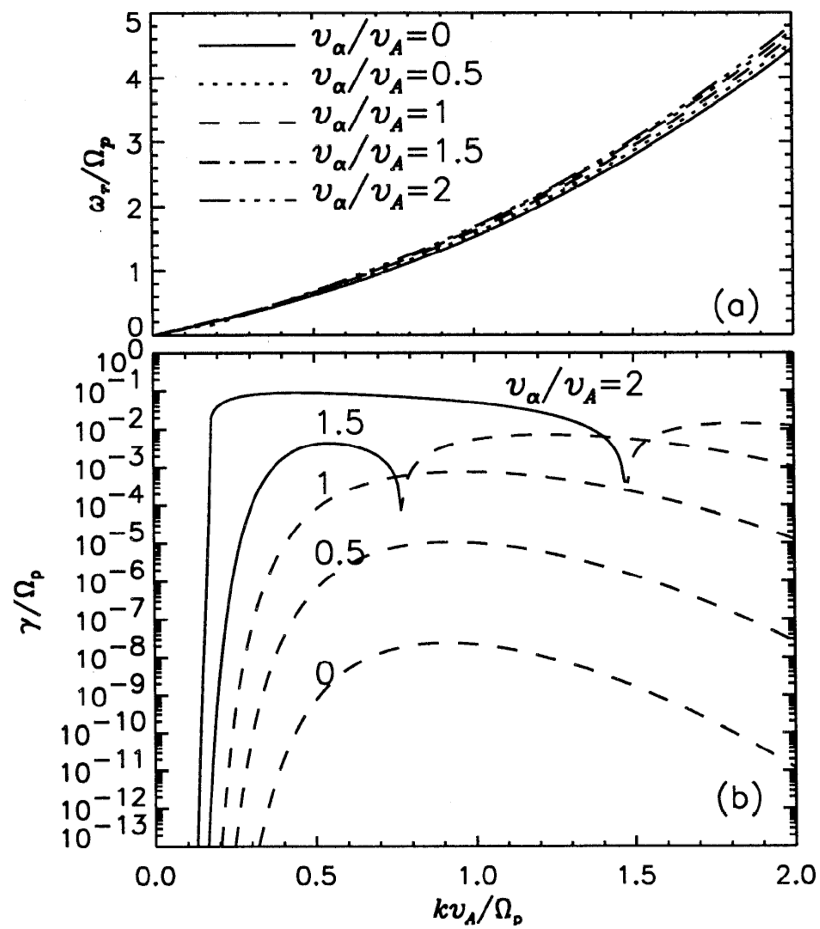
- The scale-invariant of the energy transfer rate per mass unit

$$\epsilon \sim \frac{(\delta v(l))^2}{\tau_s} \qquad \tau_s \sim \frac{l}{\delta v} \text{ is the shear time scale}$$

$$\longrightarrow \quad \delta v(l) \sim \epsilon^{1/3} l^{1/3} \quad \longrightarrow \quad P(k) \sim k \delta v^2(l)$$

$$P(k) \sim k^{-5/3}$$ For inertial range

The plasma becomes unstable when $\frac{v_\alpha}{v_A} \gtrsim 1$



$\frac{n_\alpha}{n_p} = 0.05$ and $\beta_p = \beta_\alpha = 0.25$

Dashed line: damping rate

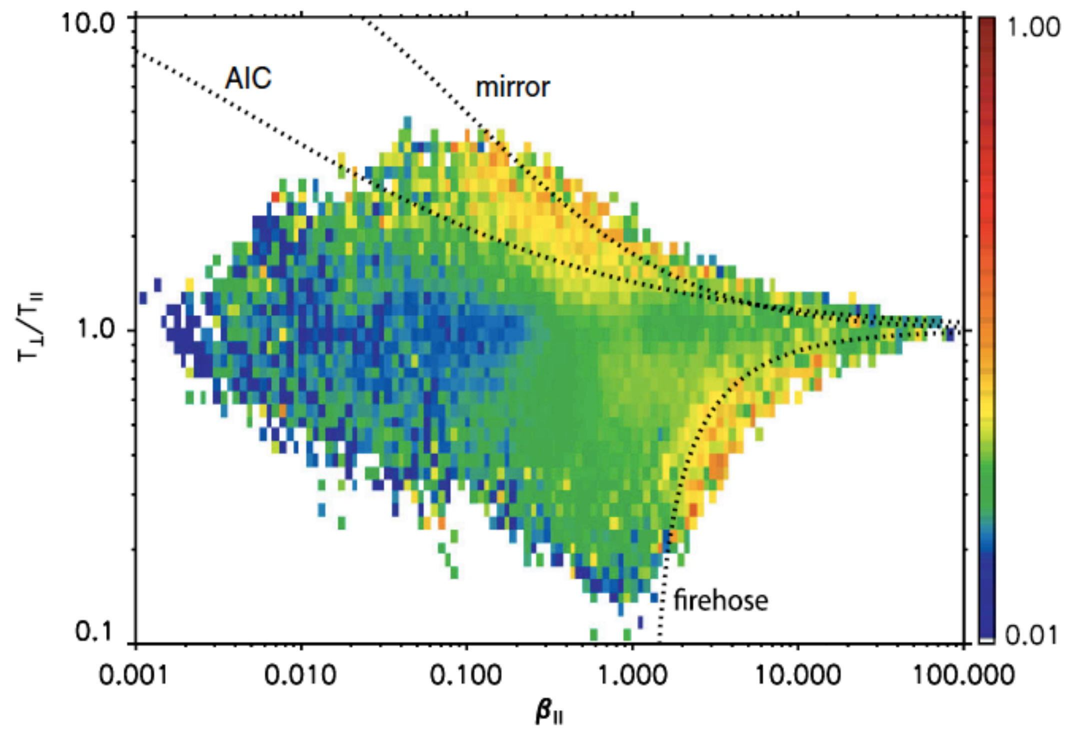
Solid lines : growth rate

$\frac{v_\alpha}{v_A} \gtrsim 1$ is the threshold for magnetosonic instability

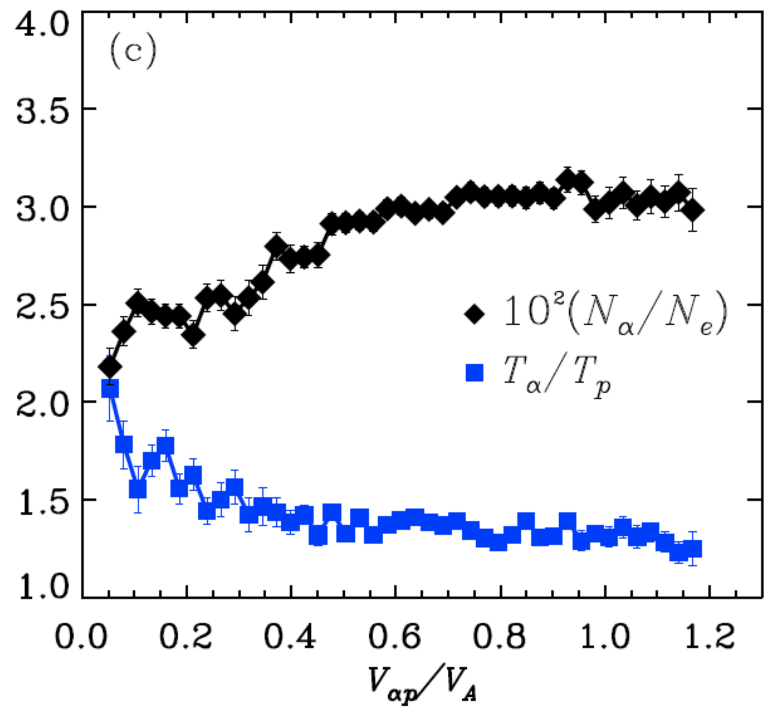
Li. X and Habbal (2000)

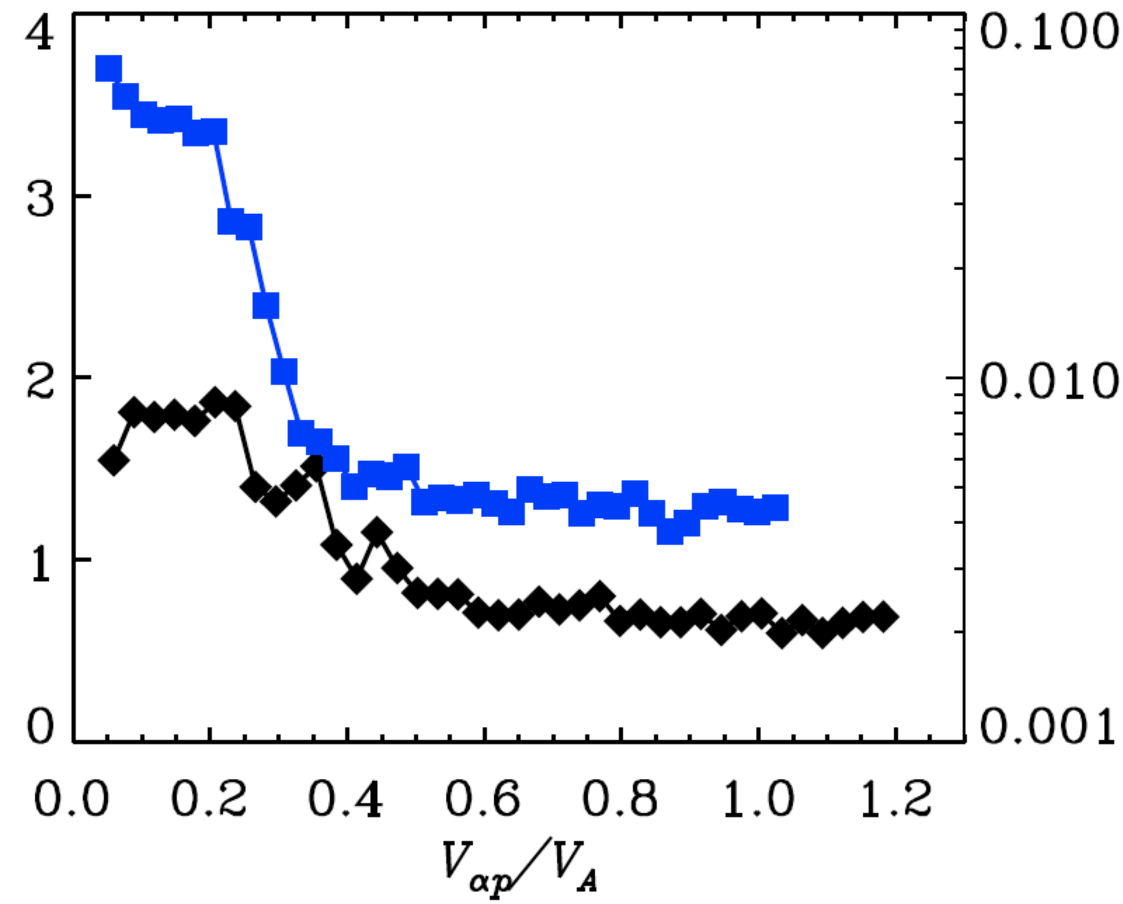
Possibility that waves are simply excited due temperature anisotropy driven instability.

However, ...



- \frac{T_{\perp\alpha}/T_{\parallel\alpha}}{T_{\perp p}/T_{\parallel p}} > 1



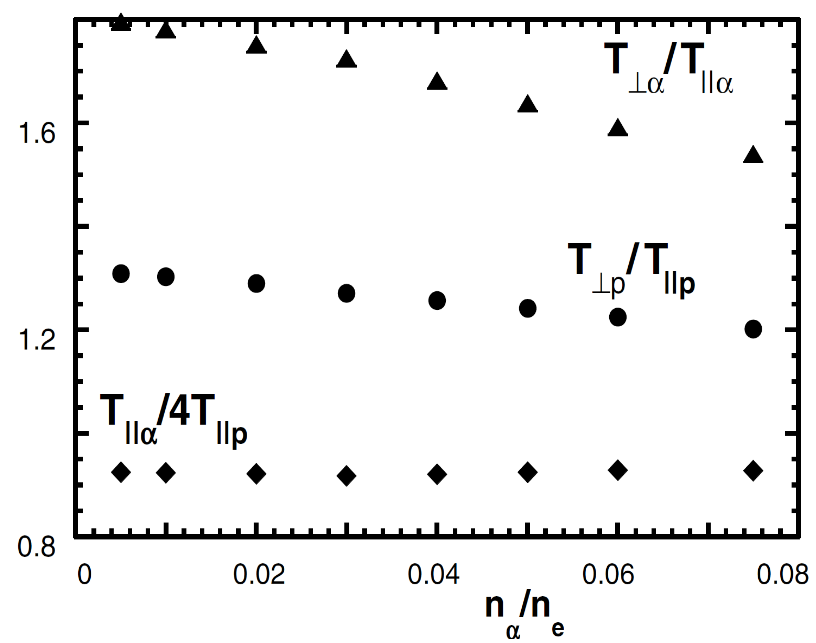


4
3
2
1
0
0.100
0.010
0.001
0.0 0.2 0.4 0.6 0.8 1.0 1.2
$V_{\alpha p}/V_A$

Other scenario based on ion scattering by Alfvén-cyclotron waves

- Negative correlation between the temperature anisotropy of ions and the relative alpha particle density.

- The simulation also predicts the negative correlation between $\frac{T_\alpha}{T_p}$ and $\frac{N_\alpha}{N_e}$



Is there a strong evidence of ion heating by the so-called AIC waves via resonant wave-particle interactions ?

Gary et al. 2006

One possible scenario….

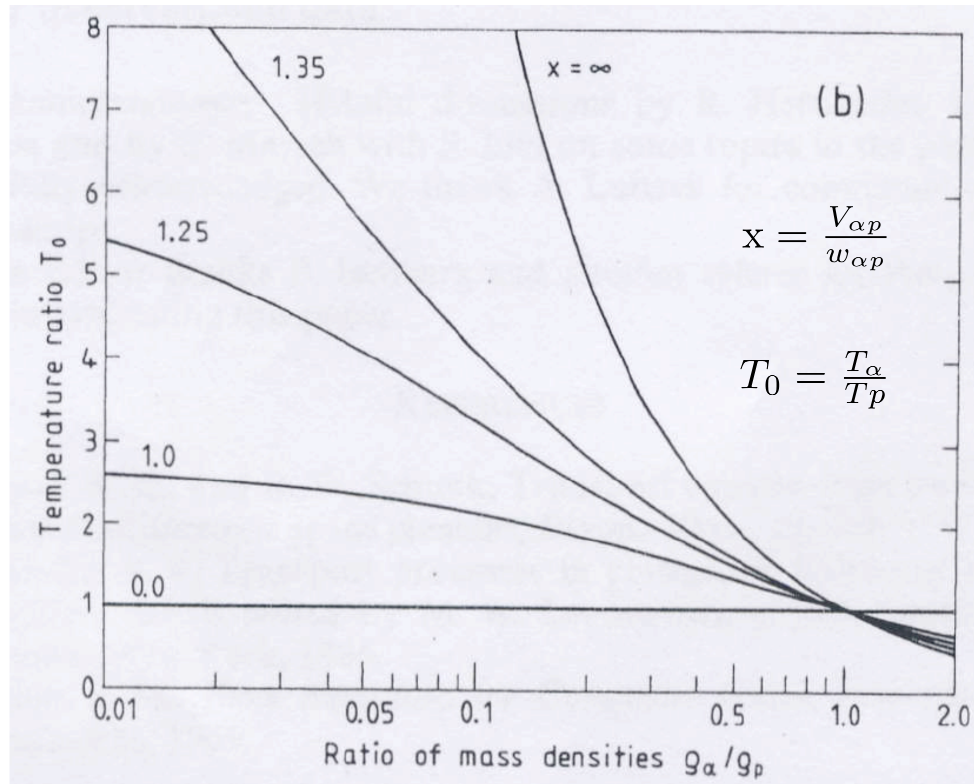
<u>Helium ion heating by collisions (no wave dissipation)</u>

$$w_{\alpha p} = \sqrt{{v_{th\alpha}}^2 + {v_{thp}}^2}$$

- Assuming two ion drifting Maxwellian VDFs

- Assume there is an external force making the ion speed difference.

- Helium ions can be heated by collisions with proton if the ion differential speed is higher than 0 (i.e., the temperature equilibration, $T_0 = \frac{T_\alpha}{T_p} > 1$

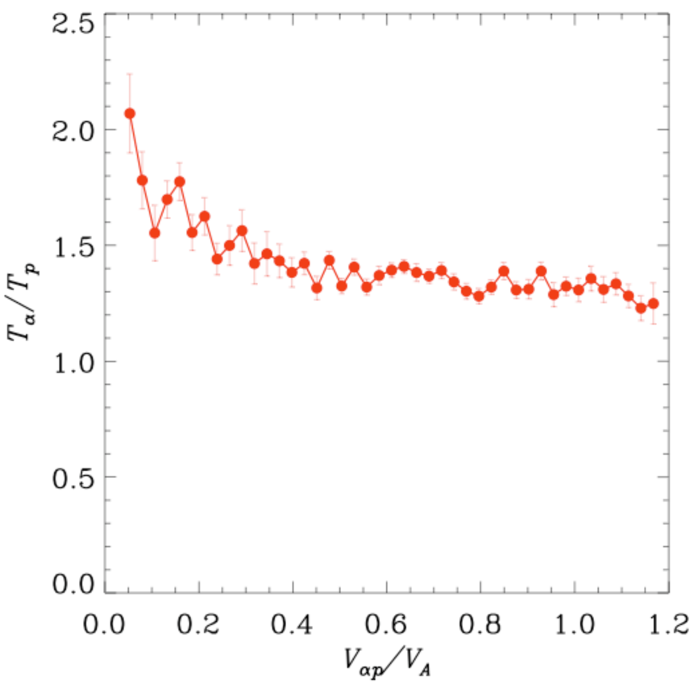


We expect that T_0 increases with $x = \frac{V_{\alpha p}}{w_{\alpha p}}$

Hernandez and Marsch 1985

However……

This is not the case especially when $\frac{V_{\alpha p}}{V_A} \geq 0.6$, the temperature ratio is roughly constant despite the increase of ion differential speed



Therefore, one has to think about another scenario!

Solar wind turbulence